Renewable and Sustainable Energy Reviews 37 (2014) 560–568

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

State-of-the-art cuttings transport with aerated liquid and foam in complex structure wells

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A R T I C L E I N F O

Article history:
Received 10 June 2013
Received in revised form
24 April 2014
Accepted 17 May 2014
Available online 7 June 2014

Keywords:
Cuttings transport
Hole cleaning
Aerated liquid
Foam
Key parameter
Mechanical model
Complex structure well

A B S T R A C T

Both aerated liquid and foam drilling as underbanlanced drilling candidates have obtained the rapid development to better protect the reservoir. Due to the presence of highly-deviated and horizontal section of complex structure wells, if the fluid velocity is lower than a critical value in annulus, cuttings will accumulate and eventually develop cuttings bed, and may result in severe problems such as stuck pipe, higher torque and drag, and poor cementing quality. Here, the sensitive analyses, empirical correlations and mechanical models for cuttings transport with aerated liquid and foam were reviewed. Studies indicate that cutting parameters, fluid parameters, operational parameters and formation parameters have effects on cuttings transport, and fluid flow rate and rheology are mainly controlled parameters. Models for aerated liquid include particle movement model, maximum cuttings volume model, optimal gas and liquid flow rate model. Models for foam include vertical-section model, two-layer model, three-layer model, three-segments model and critical velocity model. We suggest that the future researches will mainly focus on comprehensive experiments with advanced flow loops, flow simulations, mechanical models, hole-cleaning techniques and hole-cleaning optimizing system.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.05.047
1364-0321/

1. Introduction

Due to the rapid development of China's economy, the growing number of crude oil demands is presented. As shown in Fig. 1, the ratio of import and consumption has broken through 50% from the year 2008, and the contradiction between crude oil supply and demand becomes more and more obvious. Meanwhile, the mature oilfields in the east still serve as the main contributor to the oil production, and account for about two-thirds of China's crude oil production. As a result, enhancing oil recovery of these mature oilfields is still the key to increasing or stabilizing oil production.

Complex structure well has been an effective way to enhance oil recovery of mature oilfields by using the horizontal well and multilateral horizontal well [2]. During the process of drilling, if conventional drilling fluids are used, the hydrostatic pressure will be more than the formation pressure, which leads to lost circulation and serious pollution in the reservoir, especially in low-pressure reservoir or depleted reservoir. The aerated liquid and foam drilling can overcome these problems, but the performances of cuttings transport with aerated liquid and foam are critical in the highly-deviated and horizontal section. In this case, poor hole cleaning may result in stuck pipe, reduced rate of penetration (ROP), transient hole blockage leading to lost circulation, excessive drill pipe wear, extra cost for special drilling fluid additives and wastage of time by wiper trip maneuvers [3]. As a result, cuttings transport has continued to be a subject of interest to researchers and engineers.

Initially, experimental investigations were the major methods to observe cuttings-transport phenomenon and analyze the effects of various parameters on cuttings transport with a gas–solid–liquid three-phase flow. Therefore, many institutions and universities established simulated flow loops, such as BJ Services [3], Institut Français du Pétrole [4], Japan National Oil Corporation (JNOC) [5], Petrobras [6], Tulsa University Drilling Research Projects (TUDRP) [7], Middle East Technical University (METU) [8]. Meanwhile, in recent years, computational fluid dynamics (CFD) software [9] is also applied to simulate the cuttings-transport behavior in different conditions, and provides some additional information that experimental observations and filed tests are either difficult or impossible to obtain. These studied parameters which affect cuttings-transport behavior can be divided into four different groups based on the study by Ali [10]. The first group consists of cutting parameters such as cutting density, cutting shape and size, and cutting concentration. The second group consists of fluid parameters, i.e. fluid viscosity, fluid density, and fluid flow rate. The third group consists of operational parameters including inclination, pipe rotation speed, annuli size, and eccentricity. The fourth group consists of formation parameters such as temperature, pressure, and porosity.

To describe cuttings-transport efficiency quantitatively, a large number of empirical correlations and mechanical models were developed, and two types of parameters were used as target variables [11]. The first type indicates the amount of annular cuttings under a given drilling condition. Bed height (BH) [3], equivalent cuttings-bed height [12], dimensionless cuttings-bed height (DCH) [13], cuttings concentration (CC) [14], the ratio of cuttings bed area to wellbore area (RCW) [15], dimensionless cuttings-bed sectional area [16] are typical examples. The second type shows the required annular velocity to keep a minimum number of cuttings in a well. There are different names, such as required flow rates (RFV) [17], minimum foam volumetric requirement [18], maximum volume of cuttings [19], critical superficial gas velocity [20], critical foam velocity [21], optimum foam velocity (OFV) [22], and critical gas-flow rate [23].

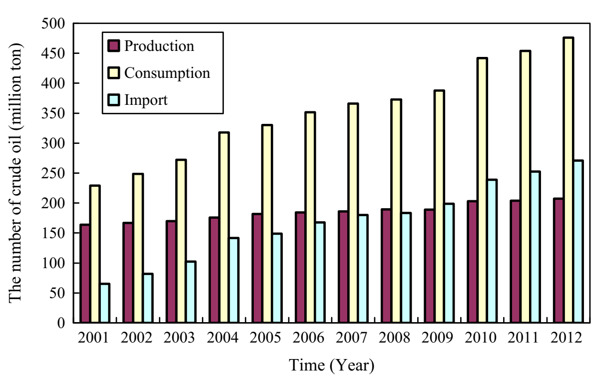

Fig. 1. Statistics of China's crude oil production, consumption and import [1].

2. Cuttings transport using aerated liquid

2.1. Effects of key parameters on cuttings transport with aerated liquid

Based on the previous experimental observations, there are many factors that affect the ability of the drilling fluid to efficiently carry cuttings and provide optimal hole cleaning, and some of such factors include liquid and gas velocities, inclination, pipe rotation, gas–liquid

Table 1
Effects of liquid/gas velocity on cuttings transport with aerated liquids.

Source	Gas velocity	Liquid velocity	Methods	Conclusions
Li and Walker [3]	6–36 m^3/h	6–36 m^3/h	BJ services, 12.7 × 6.0 cm	Carrying capacity increases dramatically for the in-situ liquid velocity larger than the critical value, and increasing liquid flow rate results in a lower cuttings-bed height
Naganawa et al. [5]	20–70 m^3/h	0.2–0.5 m/s	JNOC, 12.7 × 5.1 cm	Air injection can reduce significantly critical flow rate, and a small effect is presented in wavy stratified flow
Ozbayoglu et al. [8]	0.3–36 m/s	0.3–3 m/s	METU, 7.4 × 4.7 cm	Increasing gas flow rate or liquid rate can improve cuttings transport
Zhou et al. [12,24]	0–34 m^3/h	18–34 m^3/h	TUDRP, 15.2 × 8.9 cm	Gas injection has both positive and negative effects on hole cleaning depending on other flow parameters. The accumulation of cuttings is very sensitive to the liquid flow rate
Avila et al. [23]	11–91 m^3/h	45–114 m^3/h	TUDRP, 20.3 × 11.4 cm	Cuttings concentration is decreased by air injection
Osaouei [25]	0.3–36 m/s	0.3–3 m/s	METU, 7.4 × 4.7 cm	Carrying capacity of water-gas mixture is raised dramatically with the increase at liquid flow rate

ratio, well depth, cuttings size, ROP, flow regime, temperature and pressure. The consistent conclusions are drawn as follows:

(1) Increasing liquid velocity or gas flow rate can improve hole cleaning, and the liquid is the dominating parameter for cuttings transport. Gas injection accelerates the liquid phase, and the positive or negative effect is dependent on other flow parameters (shown in Table 1). Obviously, how to optimize the combination of gas and liquid flow rate is an important issue.
(2) Cuttings is difficult to remove with the increase of inclinations when inclinations vary from 30° to 60°, but the most severe inclination for cuttings transport cannot be determined (shown in Table 2). Also, much work will be conducted for inclinations between 20° and 70° [25].
(3) Pipe rotation has a positive effect on cuttings transport, but the level of enhancement depends on rotary speed, gas injection velocity and inclination (shown in Table 3). In addition, the pipe dynamic behavior such as orbital motion and steady state vibration should be considered.
(4) Increasing gas–liquid ratio (GLR) results in a larger cuttings-bed height [26], especially when the GLR is greater than 0.5 [3], but Zhou et al. [12] indicated that GLR has negative or positive effects on cuttings transport depending on other flow parameters, and recommended that higher GLR is applied to investigate the impact of gas injection on cuttings transport.
(5) The return velocity tests are performed with water at 700 and 1270 m depths, and the result shows that average return velocities are higher in 700 m tests, where the gas is more expanded [6].
(6) Particle diameter tested with 1.4 and 5.78 mm has a minor effect [6], but theory analysis [27] shows small-size cuttings are easier to be transported by high-viscosity fluid when cuttings size varies from 1 to 6 mm.
(7) Total cuttings concentration in annuli increases with the increase of ROP [7,8,25]. Also, the minimum gas and liquid flow rates increase with an increase in ROP for the same cuttings size [7], and are presented under a air–water intermittent flow pattern [7,28].
(8) Elevated temperature causes a significant increase in cuttings concentration at given flow conditions [12,24], but temperature effect on aerated drilling fluid is achieved by changing the viscosity and surface tension of liquid phase [29]. However, the effect of pressure (up to 3.45 MPa) on cuttings concentration is insignificant [12,24].

2.2. *Empirical correlations of cuttings transport with aerated liquid*

Li and Walker [3] thought of the critical velocity as a function of annuli size, cuttings size and density, local gravity, mixture density and rheology, liquid hold up and pipe eccentricity. Then, the fluid velocity in the open area (Fig. 2) is assumed to be equal to the critical velocity,

Table 2
Effects of inclination on cuttings transport with aerated liquids.

Source	Inclination	Methods	Conclusions
Li and Walker [3]	30–90°	BJ services, 12.7 × 6.0 cm	The highest minimum in-situ liquid velocity is presented around 60°
Naganawa et al. [5]	30–90°	JNOC, 12.7 × 5.1 cm	The most severe inclination for cuttings transport is horizontal
Vieria et al. [7]	80–90°	TUDRP, 20.3 × 11.4 cm	The effect of the inclination is negligible for the near horizontal case
Avila et al. [23]	30–60°	TUDRP, 20.3 × 11.4 cm	Volumetric cuttings concentration increases with the increase at inclination, and the performance of carrying cuttings reduces

Table 3
Effects of pipe rotation on cuttings transport with aerated liquids.

Source	Pipe rotation	Methods	Conclusions
Ozbayoglu et al. [8]	0–120 rpm	METU, 7.4 × 4.7 cm	As pipe rotation increases from 80 to 120 rpm, cuttings transport is slightly improved in a lower gas rate, but when increasing gas-flow rate, there is no further contribution of pipe rotation on cuttings transport
Mendez [20]	unknown	TUDRP	Pipe rotation decreases critical superficial gas velocity for tested fluids and flow rates
Avila et al. [23]	40–140 rpm	TUDRP, 20.3 × 11.4 cm	At the angle of 30°, a high cuttings concentration is emerged with the increase of rotary speed. At 45°, pipe rotation has both positive and negative effect on cuttings transport. At 60°, increasing pipe rotation from 40 to 110 rpm helps hole cleaning
Osaouei [25]	0–120 rpm	METU, 7.4 × 4.7 cm	By increasing rotation speed, total concentration of cuttings, including stationary and moving particles, is not considerably changed in horizontal section

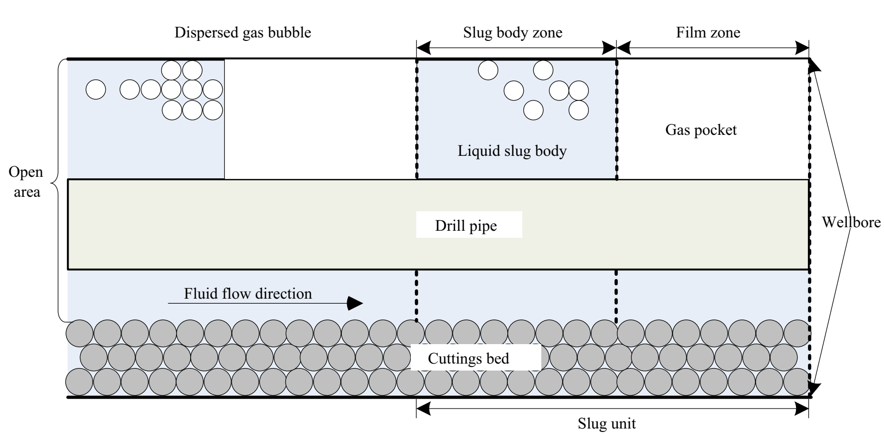

Fig. 2. Schematic representation of slug flow [27].

and the cuttings- bed height can be found. Mendez [20] proposed the correlation of the critical superficial gas velocity required to have no cuttings bed with pipe rotation, and the correlation is a function of liquid superficial Reynolds number and rotational Reynolds number. Avila et al. [23] developed the correlations to predict critical gas-flow rate and cuttings concentration, and considered the effects of inclination, liquid superficial Reynolds number, rotational Reynolds number, and gas superficial velocity, but the correlations were valid for inclinations from 30° to 60° from vertical and for well without centralizers. Due to these correlations limited in a special condition, mechanical models were also studied.

2.3. Mechanical models of cuttings transport with aerated liquid

The particle movement model, maximum cuttings volume model, optimal gas and liquid flow rate model are three typical models applied to depict the cuttings-transport behavior with aerated liquids, and each model is specified as follows.

Zhou et al. [12,29] and Zhou [24,27] developed the particle movement model based on the mechanical equilibrium acting on a particle on the cuttings-bed surface (Fig. 3), and these forces included gravity, buoyancy, lift and drag. Meanwhile, Van der Waals force and plastic force have been considered for the conventional drilling fluid [11,30]. Then, as shown in Fig. 2, mass and momentum conservation equations are established for the two-layer model which is comprised of stationary cuttings bed and an upper layer. Finally, the two models are connected by the frictional pressure loss, and can determine the minimum fluid flow velocity and cuttings concentration. But the models ignore the slip between cuttings and fluid, and slug flow pattern is only considered in the open area.

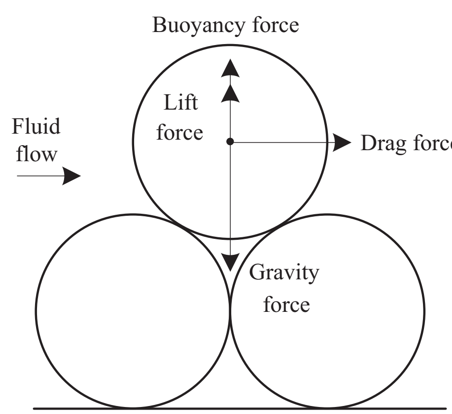

Fig. 3. Forces acting on a particle on the cuttings-bed surface.

Guo et al. [19,31] defined the carrying capacity of the aerated drilling fluid as the maximum volume of cuttings and that mixture velocity was greater than the sum of the terminal or slip velocity and required cuttings-transport velocity. Rittenger's equation was used to calculate the terminal slip velocity of vertical flat particles. The required cuttings-transport velocity is equal to the ratio between ROP and allowable cuttings concentration. But the model can be only applied for vertical wells and low inclined wells.

Ozbayoglu [32] assumed that liquid phase was the major contributor for cuttings transport, and gas phase only influenced the bottom hole pressure. For the different flow pattern including bubble flow, slug flow, churn flow and annular flow (Fig. 4), mechanistic models are introduced to determine the velocity distribution, pressure drop losses and transitional conditions for various flow patterns. Based on the bottom hole pressure and effective hole cleaning, the introduced models can be used to calculate the optimal gas and liquid flow rate, and are limited in the vertical and low inclination wells.

These mentioned models have the following common disadvantages:

- Pipe rotation is not considered.
- Drill cuttings have spherical shapes with uniform sizes.
- Mass and energy exchanges between wellbore and reservoir are ignored.
- The uncertainty is presented in selection of appropriate flow regarding two phases.

3. Cuttings transport using foam

3.1. Effects of key parameters on cuttings transport with foam

The past experimental and CFD studies have demonstrated that foam velocity and quality, inclination, pipe rotation, ROP, pressure,

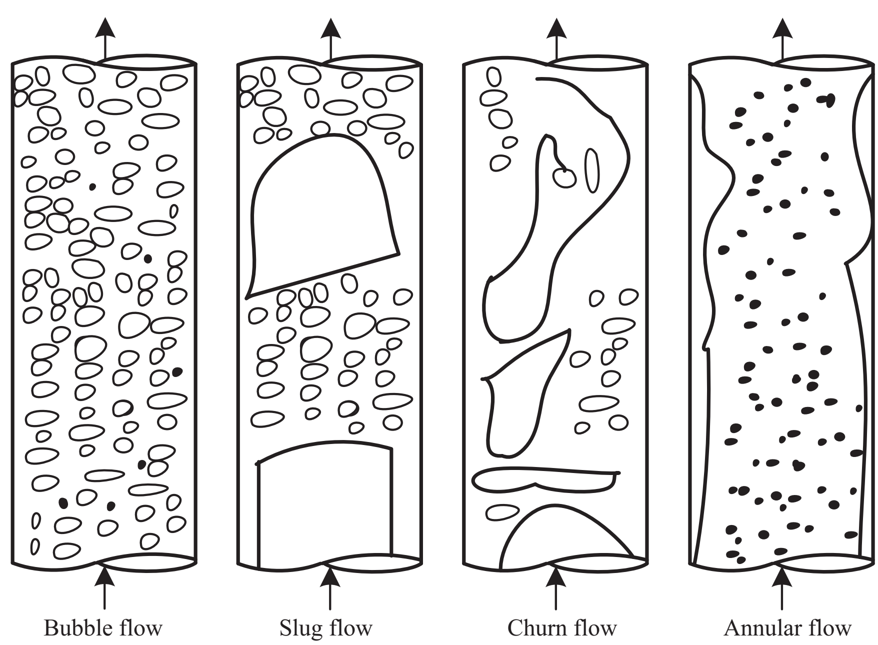

Fig. 4. Flow patterns for upward vertical pipes [32].

temperature, eccentricity, annuli size, cuttings size, and viscosity have the impacts on cuttings transport. The consistent conclusions are listed as follows:

(1) Turbulent effect is helpful to cuttings transport; thus, cuttings-bed height is very sensitive to foam velocity when the velocity reaches the critical value (shown in Table 4). Liquid flow rate plays an important role, especially in the lower-foam-quality tests [42], but increasing gas flow rate can help cuttings transport better than increasing the liquid flow rate [39].
(2) The mechanism of different inclinations is difficult to be determined accurately due to different experimental conditions and complex cuttings-transport behavior, but it is sure that the toughest section for hole cleaning is the build section rather than the vertical or the horizontal section (shown in Table 5).
(3) The performance of cutting transport is improved with increase of foam quality, but stationary cuttings-bed height increases. Meanwhile, the higher efficiency of cuttings transport is emerged in higher foam quality when experiments are used with pipe, but a contrary conclusion is obtained with annuli (shown in Table 6). Higher foam quality is recommended for horizontal well, which can save chemicals and improve cuttings transport [39].
(4) CFD simulations show pipe rotation produces the secondary reflux of foam fluid in annuli, which has a positive effect on destroying cuttings bed [43], and pipe rotation by experiments

Table 4
Effects of foam velocity on cuttings transport with foam.

Source	Foam velocity	Foam quality	Methods	Conclusions
Wang [9]	3.6–10.8 m^3/h	0.7	CFD, 8 × 3 cm	At the given cuttings size and foam quality, cuttings volume fraction decreases with increase in foam flow rate
Duan et al. [14] and Duan [33]	0.6–1.8 m/s	0.6–0.9	TURDP, 14.6 × 8.9 cm	An increase in foam velocity noticeably decreases cuttings concentration using high quality foam (0.9)
Wang et al. [34]	0.6–1.2 m/s	0.5–0.9	CFD, 21.59–11.43 cm	In eccentricity annuli, the flow core is situated in the center of the big gap, and is responsible for cuttings transport. The cuttings-bed height decreases with the increase at foam velocity
Ozbayoglu [35] and Ozbayoglu et al. [36]	0.3–4.8 m/s	0.7–0.9	TUDRP, 20.3 × 11.4 cm	A high foam flow velocity are required to prevent a thick cuttings bed for all foam qualities
Capo et al. [37]	0.9–1.5 m/s	0.7–0.8	TUDRP, 20.3 × 11.4 cm	High foam velocity helps cuttings transport, and can prevent cuttings-bed development at high ROP
Chen et al. [38] and Chen [39]	0.6–1.8 m/s	0.7–0.9	TURDP, 14.6 × 8.9 cm	The accumulation of cuttings in the annuli is not sensitive to increasing flow velocity until a critical velocity is reached

Table 5
Effects of inclination on cuttings transport with foam.

Source	Inclination	Methods	Conclusions
Herzhaft et al. [4] and Saintpere et al. [40]	0–90°	Institut Français du Pétrole, pipe	Poor hole cleaning is situated between 45° and 60° when characteristic concentration is equal to 4.6
Ozbayoglu [35] and Ozbayoglu et al. [36,41]	70–90°	METU/TUDRP, 20.3 × 11.4 cm	There is a little effect of inclination in the range of 70–90°
Capo et al. [37]	45–65°	TUDRP, 20.3 × 11.4 cm	Cuttings are the most difficulty to be removed at hole angle approximately 55°
Martins et al. [42]	45–90°	Petrobras, 10 × 4.2 cm	A poorer cleaning performance is observed in the inclined than in the horizontal wells

Table 6
Effects of foam quality on cuttings transport with foam.

Source	Foam qauality	Methods	Conclusions
Herzhaft et al. [4]	0.84–0.96	Institut Français du Pétrole, pipe	Efficient cuttings-transport with foam is strongly dependent on its quality, and the efficiency increases with the increase of foam quality
Wang [9]	0.75–0.95	CFD, 8 × 3 cm	At the given cuttings size and foam velocity, increasing foam quality results in the growth rate of cuttings fraction volume
Duan [33] and Duan et al. [14]	0.6–0.9	TUDRP, 14.6 × 8.9 cm	Decreasing foam quality from 0.7 to 0.6 significantly increases cuttings concentration, but a contrary result is shown when increasing foam quality from 0.7 to 0.9 at a low or medium foam velocity
Wang et al. [34]	0.5–0.9	CFD, 21.59 × 11.43 cm	Cuttings-bed height reduces with the increase of foam quality
Ozbayoglu [35]	0.7–0.9	TUDRP, 20.3 × 11.4 cm	As the foam quality increases at a given flow rate, stationary cuttings- bed height also increases
Capo et al. [37]	0.7–0.8	TUDRP,20.3 × 11.4 cm	A lower in situ cuttings concentration is observed with the decrease of foam qualities, but a low quality foam can improve cuttings-transport efficiency
Chen et al. [38] and Chen [39]	0.7–0.9	TUDRP, 14.6 × 8.9 cm	Cuttings concentration decreases as foam qualities increase from 0.7 to 0.9
Martins et al. [42]	0.6–0.95	Petrobras,10 × 4.2 cm	High quality foams have an excellent performance of cuttings transport
Yuan [43]	0.7–0.9	CFD, 7.5 × 3.2 cm	The ability to carry cuttings improves with the increase of foam quality

significantly decreases cuttings concentration in a horizontal annulus for foam qualities from 0.6 to 0.9 [14,33].

(5) Cuttings concentration slightly decreases with the increase in pressure or the decrease in temperature when foam quality is kept constant [14,33], but Chen et al. [38] and Chen [39] indicate that increasing pressure or decreasing temperature causes a slight decrease in cuttings concentration for 0.8 and 0.9 quality foams, and the effect is negligible for 0.7 quality foam.

(6) Cuttings is easier to be carried with increase in pipe eccentricity or big annular gap, and cuttings bed may be formed for cutting size more than 2 mm [9,43]. Also, a higher ROP results in a high cuttings accumulation and in-situ cuttings concentration in the annulus [37].

(7) Higher viscosity of drilling fluid causes a thicker cuttings bed, and when a less viscous fluid is used, bed development is prevented even at a lower annular velocity [36]. In addition, by adding HEC polymer into the foam system, cuttings concentration in the annuli decreases [39,44].

3.2. Correlations and models of annular cuttings

In order to predict the annular cuttings, the following empirical correlations or mechanical models can be chosen in different conditions:

- Empirical correlations.
- Vertical-section models.
- Two-layer models.
- Three-layer models.
- Three-segment models.

3.2.1. Empirical correlations

As shown in Table 7, the correlations consider fluid rate, ROP, annuli size, inclination, foam density and rheology, pipe rotation and other parameters. These correlations can provide the simplified algorithm for the engineers and check the accuracy of the mechanical models, but they are limited in narrow regions.

3.2.2. Vertical-section models

As shown in Fig. 5, Li [45] and Li and Kuru [46] established the unsteady model to estimate cuttings concentration based on the mass and momentum equations for foam and solid. In this model mass influx rates of water, oil and gas from reservoir are defined as the source term. The real gas law is applied to determine the foam density. A new rheology equation is regressed by using the data of Sanghani and Ikoku [47]. The effect of cuttings is also incorporated into the frictional factor. Boundary conditions such as ROP, gas and liquid injection rates at the surface, and the back pressure in the annuli are specified, but the model has the following shortcomings:

- Pipe rotation is ignored.
- Cuttings have spherical shapes with uniform sizes.
- Inflowing reservoir fluids are instantaneously accelerated to mean foam velocity.
- Reservoir fluids flowing into the wellbore commingle with foam completely.

3.2.3. Two-layer models

As shown in Fig. 6, the two-layer unsteady model is comprised of suspended layer, stationary or mobile cuttings bed, and the parameters are dependent on time. All the models are composed of mass and momentum conversation equations which describe the flowing conditions of cuttings and foam in the suspended layer, and combined with other closure equations these models can be solved, but the differences are which equations and factors are chosen and considered in the models.

Li [45] and Li and Kuru [48] analyzed the effects of mass influx of water, oil, and gas from the reservoir, critical deposition velocity,

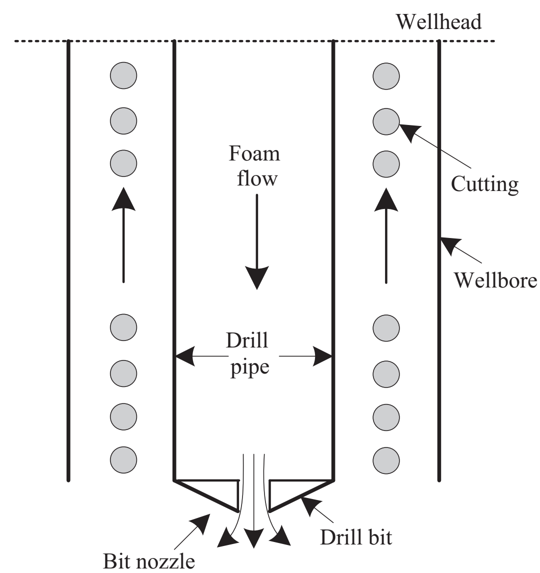

Fig. 5. Schematic representation of vertical-section model.

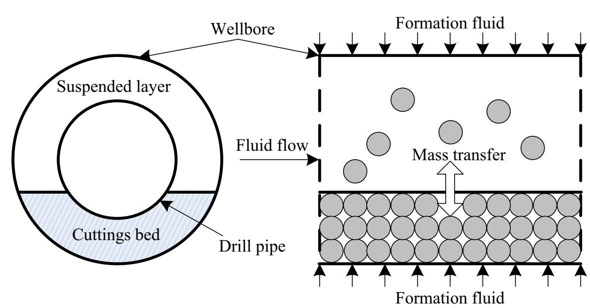

Fig. 6. Schematics of two-layer model [48].

Table 7
Empirical correlations of annular cuttings.

Source	Goal	Methods	Foam quality	Characteristics/main factors	Applicability
Duan et al. [14]	BH/CC	TUDRP, 14.6 × 8.9 cm	0.6–0.9	Foam quality and rheology, critical pressure drop, and wellbore geometry parameters	Horizontal well
Ozbayoglu et al. [15] and Ozbayoglu [35]	RCW	TUDRP, 20.3 × 11.4 cm	0.7–0.9	Foam Reynolds number, Froude number, and ratio of cutting volume /annular volume	From 70° to 90°
Capo et al. [37]	RCW	TUDRP, 20.3 × 11.4 cm	0.7–0.8	Inclination, foam rheology and density, cuttings density and size, local gravity, flow rate, and foam quality	Intermediate inclined well
Martins et al. [42]	DCH	Petrobras, 10 × 4.2 cm	0.6–0.9	Annuli size, foam rheology, velocity and density	Horizontal well

mass transfer between layers, and foam as a compressible fluid, and developed the unsteady model to predict dimensionless cuttings-bed height. Based on the above models, Osunde [49] and Osunde and Kuru [50] considered slippage between the foam and cuttings, and used the model to calculate cuttings concentration. Wang et al. [13] and Yan et al. [51] considered mass transfer between layers and the compressibility of foam completely depending on gas phase. Formation fluid flow obeys Darcy's law without considering the dissolution of gas in liquid and oil, and then the model is established to predict dimensionless cuttings-bed height. However, some factors ignored or assumed in these models are as follows:

- Pipe rotation is ignored.
- An isothermal process is assumed.
- Cuttings bed is kept stationary.
- Cuttings-bed concentration, ROP and rheological properties are constant.
- Foam is a fluid with a homogeneous property in any cross-sectional area.
- Cuttings have uniform size, shape and velocity in any cross-sectional area.
- Inflowing reservoir fluids are instantaneously accelerated to mean foam velocity.
- Reservoir fluids flowing into the wellbore commingle with foam completely.

3.2.4. Three-layer models

As shown in Fig. 7, the three-layer steady model which is comprised of suspended layer, mobile and stationary cuttings bed is independent of time. The model includes the two basic equations of mass balance and momentum balance. The mass balance equation describes the mass variation of particle and foam, and the momentum equation depicts the sum of forces acting on the suspended layer, mobile and static cuttings-beds. Combined with other closure equations the basic equations can be solved.

Ozbayoglu [35] and Ozbayoglu et al. [36,41] developed the generalized rheological models for Newtonian, power law, Bingham plastic, and yield power law. The layer model considered slip between cuttings and fluid, in-situ concentration of mobile bed, mixture viscosity of cuttings and fluid, and could be used to calculate the ratio of bed area and wellbore area. Amna et al. [52] considered the gravity, buoyancy, lift and drag acting on the particle on the stationary-bed surface, and formed a particle movement model to estimate mobile cuttings-bed velocity. Using the layer model the cuttings-bed height can be determined. However, these models need to be further improved, and these factors should be considered as follows:

- Pipe rotation and mass transfer between layers are ignored.
- Suspended layer without cuttings.

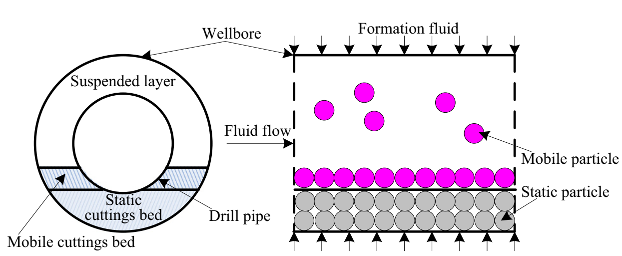

Fig. 7. Schematics of three-layer model.

- Foam flow is isothermal and steady.
- Drill cuttings have uniform size, shape and velocity.
- Energy and mass transfer between wellbore and reservoir.

3.2.5. Three-segment models

During the process of drilling, cuttings transport from bottom to ground is a complete process, and the inclination covers from vertical to horizontal. Based on the cuttings-transport mechanism in the various inclinations, Cho [53] established the three-segments model with conventional drilling fluid. Similarly, for foam drilling, Cheng and Wang [16] made all the wellbore divided into three segments including vertical section (0–30°), transient section (30–60°), and horizontal section (60–90°). The steady vertical-section model, two-layer model and three-layer model were developed to use for each section, respectively. These models can be applied to describe the variation of dimensionless cuttings-bed sectional area, but these assumptions are made:

- Drillpipe rotation is not considered.
- Homogeneous bubble flow is regared as the unique flow pattern.
- Compressibility of foam completely depends on gas phase.
- Cuttings have the same sphere, diameter, and uniform distribution.
- Slip effect between gas and liquid is negligible.
- Mass transfer and energy exchange between fluid and solid are ignored.

3.3. Correlations and models of critical velocity

For the empirical correlations, Okpobiri and Ikoku [18] firstly incorporated particle friction force into foam flow simulations, and developed a semi-empirical correlation which considered the effects of annular backpressure, temperature, annuli size, foam properties, cuttings characteristics, ROP, and well depth. Meanwhile, they pointed out that the foam velocity required by effective cuttings-transport at the bottom of hole was greater than the settling velocity of cuttings by 10%, and Krug and Mitchell [17] recommended the RFV was 0.46 m/s. However, these empirical correlations are suitable for the vertical well, and some correlations should be developed for the highly-deviated and horizontal well. For the mechanical models, Li and Kuru [21] modified Oroskar and Turian's correlation [54] to determine critical deposition velocity, and a new model based on the unsteady two-layer model [48] could be used to calculate CFV. Later, they [22] introduced the vertical-section model [46] and the equations about optimum back pressure and well depth, and the new model could determine the OFV by neglecting hole size. It is obvious that the mechanical models have the same shortcoming with the mentioned two-layer model and vertical-section model.

4. Future researches and technology needs

4.1. Flow loops and comprehensive experiments

Flow loop is an important method to determine the coefficients referred by correlations and models, but its operational conditions will affect and limit the experimental results to some extent. Therefore, high temperature and pressure, borehole enlargement and shrinkage, mass exchange of wellbore and reservoir, wellbore collapse, etc. should be gradually added to flow loop to better simulate actual downhole conditions. Also, most of the existing flow loops only can measure cuttings bed height or area and annular pressure drop, and cannot record concentration distribution of

particle. Ideally, a CCD video camera system [55,56] is introduced to track cross-sectional distribution and movement of cuttings, and determine flow pattern transition. In addition, cuttings transport is always affected by multi-factor interaction, especially when pipe is rotating; therefore, it is essential that analyzing the combined effects on cuttings transport with pipe rotation is to determine the controlling variables and further understand cuttings-transport behavior in different conditions.

4.2. Flow simulations

Flow simulation can clearly depict the cuttings concentration, cuttings distribution, fluid velocity, and fluid distribution. Especially for the flow field simulation, it can supplement for the experiments. Wang et al. [34] and Yuan [43] applied Euler multi-phase model of fluent to analyze the effects of foam quality, eccentricity and annuli size and other parameters on foam velocity and cuttings transport, and the results were checked by experimental data. However, the simulation with aerated liquid was rarely reported. As a result, more simulations will be conducted by choosing different models and setting different variable combinations, especially cuttings-transport simulations with aerated liquid.

4.3. Mechanical models

As Cho et al. [57] summarized, there seems to be two main reasons for a low predicted accuracy of most of mechanical models. On one hand, researchers applied the same methodology to describe different physical phenomena, and developed a complete model suitable for the inclination from vertical to horizontal. On the other hand, use some improper concepts, simplify too many assumptions or neglect certain observed phenomena in the models. It must be said that the distribution of annular cuttings is asymmetric when drill pipe is rotating, which leads to a big error between the predicted result obtained from layer models and measured data. Meanwhile, the proper flow pattern is difficult to be determined for the aerated liquid flow. As a result, a new theory or method should be introduced into mechanical models to better depict the cuttings transport and fluid flow. In addition, the above-mentioned shortcomings or assumptions for each type of models should be concerned, and some major coefficients related to the models also make an in-depth study in annular flow conditions.

4.4. Hole-cleaning techniques

In recent years, researchers' interests mainly focus on the fiber sweep and cuttings removal tool. The former can be used to reduce the accumulation of cuttings and prevent the formation of cuttings bed, and some achievements have been made in field applications [58,59,60]. However, the flow behavior, hydraulics, and cuttings-transport efficiency are less known, and how to reasonably use with drilling fluid in different conditions needs further study. The latter which has helical grooves or blades on their surface with a negative angle can be applied to remove cuttings bed [61], and VAM Drilling Corporation has started to conduct the commercial use. But how to design a tool which can realize the combination of hole-cleaning efficiency, time saving, operational safety and wellbore quality is still a difficult challenge.

4.5. Real-time hole-cleaning optimizing system

Hole-cleaning conditions are closely related to both drilling designs and drilling operations; thus, building a real-time hole-cleaning optimizing system may be an indispensible part of intelligent drilling. The optimizing system may include a design system, data collecting system, data processing system and decision making system. The design system makes hole-cleaning problem integrated into hydraulics design, and eliminates critical inclination if possible. During the process of drilling, data collecting system can choose advanced measuring instruments to rapidly collect the available operational parameters, fluid parameters and formation parameters. Subsequently, based on these collecting data, the processing system can quickly calculate and determine the real-time hole-cleaning parameters such as cuttings bed height, cuttings concentration and cuttings transport ratio. Finally, the decision making system will conduct a comprehensive evaluation for hole-cleaning conditions, and makes a quick decision whether measures are taken to enhance hole-cleaning conditions and prevent downhole accidents, and which measures should be taken if necessary. Martins et al. [62] made an attempt to real-time monitoring of hole cleaning on the deepwater extended well, and Green et al. [63] and Lapierre et al. [64] applied real-time PWD (Pressure While Drilling) to optimize hole cleaning, but much more work is done to build an advanced optimizing system.

5. Conclusions

Due to the increasing number of complex structure wells in China, the hole-cleaning issue with aerated liquid and foam will become more and more prominent. The review showed that cuttings parameters, fluid parameters, operational parameter and formation parameter have effects on cuttings transport. But in the process of drilling, most of these parameters are uncontrolled. Fluid flow rate and fluid rheology are the major controlled parameters to keep good hole cleaning. Meanwhile, the empirical correlations and mechanical models can provide the theoretical foundation for optimizing the fluid flow rate and rheology and estimating the number of annular cuttings.

However, due to the complexity of cuttings-liquid–gas three-phase flow in complex structure wells, although major improvements have been achieved in the past several decades, but how to develop a comprehensive model depicting the cuttings transport, optimize the combination of the liquid and gas flow rates, and solve the poor hole cleaning are still difficult challenges. As a result, more researches will be conducted to further understand the cuttings-transport mechanism and better improve hole-cleaning conditions in both aerated liquid and foam drilling.

Acknowledgments

The support of National Science and Technology Major Project of China (No. 2011ZX05009-005) and the National Natural Science Foundation of China (Nos. 51174043 and 51204056) is gratefully acknowledged.

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